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Primus Green Energy

Daniel David Tocco
Worcester Polytechnic Institute

Joseph Tyler Giesecke
Worcester Polytechnic Institute

Sam Vincent Miraglia
Worcester Polytechnic Institute

Primus Green Energy

Alternative Drop-In Fuel
Economical. Practical. Local.

A 12-13 Interactive Qualifying Project Report

Submitted to the faculty of

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In partial fulfillment of the requirements for the

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By

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Daniel Tocco

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Sam Miraglia

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Joseph Giesecke

Abstract

Primus Green Energy project was an Interactive Qualifying project done by students at Worcester Polytechnic Institute to assess the projected impact of Primus Green Energy's synthetic gasoline process in the transportation sector. Their effectiveness was evaluated on the potential to reduce the United States' dependency on oil and to reduce the price of gasoline. Students calculated the ideal gasoline production for a single plant using numbers provided by Primus with biomass used as a feedstock. Other companies were researched and used to form a baseline comparison with Primus when tracking their progress and extrapolating current demonstration data to a larger scale.

Acknowledgements

We would like to thank Professor Robert W. Thompson for his time, effort, assistance, and insight as advisor over the course of the project. We would also like to thank the following individuals who corresponded with us on various subjects: Todd Keiler of Worcester Polytechnic Institute for his assistance in understanding patents and patent law; Tomi Maxted and Jerry Schranz of Beckerman Public Relations for their help in contacting Primus Green Energy; and Dr. Nan Li of Primus Green Energy for taking the time to answer questions specific to Primus' plans and operations.

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1.0 Background

1.1 Goals

The goal of this project was to assess the validity of claims made by a company called Primus Green Energy. With gasoline being as expensive as it currently is, there have been numerous attempts to replace gasoline with more cost-effective alternatives. Primus' claim to have produced a cheap synthetic gasoline almost seems too good to be true. A secondary goal of this project was to examine the prospective impact that Primus' process would have on the transportation industry.

1.2 US Fuel Consumption in the Transportation Sector

The United States has been far and away the largest consumer country of oil products for many years. The US accounts for about 44% of the world's gasoline consumption (FAQs: Natural Gas). From 2001 to 2009, excluding 2006 (as they were not the leaders in oil consumption in that year) the United States averaged about 13,500,000 more barrels of oil consumed per day than the next leading country. There is no doubt that the United States has a certain affinity for oil and gasoline, consuming roughly 21 million barrels of it a day in 2011. In order to explain the cause of such an avid "addiction" to gasoline for which the United States is known, we must investigate the policies that have been put into place by the government, as those are likely to be the primary answers. The primary reasons why we consume so much gasoline can be linked to a number of issues in the US. We are a country with low fuel taxes, low fuel efficiency requirements, and a poor public transportation system (Horton 2012). All of these flaws combine to create a perfect recipe for a gasoline obsession. There are very few obstructions that are capable of impeding our craving for gasoline, unlike in Denmark where high purchase taxes on cars reduces the number of cars sold, hence reducing the necessity for gas. In the United States, over 244 million vehicles are being used. Therefore the US has 755 cars for every 1,000 citizens. The fact that the US purchases and uses so many cars, however, does not necessarily mean high gasoline consumption. For example, Portugal has 773 cars for every 1,000 people, yet it consumed less than 45,000 barrels of gasoline a day in 2004. This equates to approximately 221.2 million cars owned in the United States and 8.12 million in Portugal in 2004. Knowing Portugal's approximate daily consumption of gasoline, the number of barrels consumed per car each day in Portugal is .0055. In the United States about 9.5 million barrels of gasoline were consumed per day in 2004 (Jegarajah & Choi, 2004), therefore the number of barrels consumed per car each day is .043. This comes out to be 12.8% more gasoline per car each day in the United States when compared to Portugal in 2004. There are several reasons for this discrepancy. It can partially be attributed to the extremely high driving rate in the United States as well as the difference in diesel fuel usage in Europe. Due to Europe's high demand for fuel efficiency they prefer diesel fuel cars to cars that use gasoline. In Europe the percentage of cars that use diesel fuel is 10 times higher. In the United States only 4% of cars run on diesel fuel whereas in Europe that number is 40%. Also, the average car in Europe is more efficient than the average car in the United States. At 32 miles per gallon the average European car is significantly more efficient than its US counterpart at less than 22 miles per gallon (Brain, 2012). The United States is far larger than Portugal, and the vehicles used in the US travel farther and require more gasoline than those of any other industrialized nation. Each US car travels an average of more than 11,618 miles per year and they acquire their gasoline from about 162,000 fueling stations. The difference can also be attributed to being a wealthy nation with low fuel taxes, low fuel efficiency requirements and a poor public transportation system in comparison with Portugal (Factbooks, 2011).

Gasoline accounts for slightly more than 64% of all energy used for transport, and 18% of total US energy consumption. In 2010 the United States consumed about 7 billion barrels of refined petroleum products and biofuels, which equates to about 19.18 million barrels per day. In 2011 we consumed similar numbers to that of 2010. In 2011 the United States used 6.87 billion barrels, which equates to 18.83 million barrels per day. In addition, in both of these years the amount of total world petroleum consumed by the United States was 22% (Deaton).

In 2011 the United States consumed about 134 billion gallons of gasoline (there are 42 US gallons in a barrel), which equates to 3.19 billion barrels. This means that we used 367.08 million gallons per day (8.74 million barrels), which is about 6% less than the record high of about 390.08 million gallons per day (142.38 billion gallons total or 3.39 billion barrels) in 2007. Through all these numbers we can evaluate the amount of gasoline used per person in 2011. Because there were about 311.8 million American people (Rosenberg, 2011) using about 367.08 million gallons per day in 2011, that is just about 1.18 gallons used per person per day (Deaton).

In addition to being the largest consumer of gasoline in the world, the United States imports the majority of its oil. Only 36% of US oil came from domestic sources in 2011. Of that domestically produced oil 11% from Alaska, while the other 89% came from various oil fields in the 48 mainland states. The other 64% of oil consumed in the US was imported. The United States had about 11.4 million barrels per day of petroleum imported from about 80 different countries. Of all the countries from which the US imported gasoline, Canada was the United

States' primary source at 24% of our imports. Mexico came second at 11% of our imports. Canada supplied us with more oil than all of the Persian Gulf countries combined, which produced 13% of our imports. Canada was the individual country that provided the United States with the most oil, however there was an entity comprised of several oil rich countries that provided a larger percentage of the United States oil imports. That accolade goes to the Organization of the Petroleum Exporting Countries or OPEC. In 2011 OPEC supplied the US with about 40% of its imported oil (Nerurkar, 2012). OPEC was founded in September, 1960 and is currently made up of 12 oil rich nations: Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates (UAE), and Venezuela. Of these nations the top 3 exporters to the US were Saudi Arabia at 11%, Venezuela at 8%, and Nigeria at 7% (Deaton).

Gasoline is not the only fuel consumed by the United States in large quantities. In worldwide operations United States passenger and cargo airlines require more than 18 million gallons of jet fuel annually, which equates to more than 430 million barrels. From 1984 to 2005 the amount of jet fuel consumed by the United States per year has increased fairly steadily. From 2006 to 2008, however, the amount of jet fuel consumed by the United States has been a bit more sporadic. The most recent data that could be found on the United States consumption of jet fuels was 1,538.56 barrels per day in 2008 (How Much Natural Gas Is Consumed in the US?, 2012).

Another major fuel of recent years is natural gas. In 2011, the US consumed approximately 24.37 Tcf (trillion cubic feet) of natural gas in 7 end uses: Electric power (7.6 Tcf, 31%), industrial (6.77 Tcf, 28%), residential (4.73 Tcf, 19%), commercial (3.16 Tcf, 13%), lease and plant fuel consumption (1.38 Tcf, 6%), pipeline and distribution (.69 Bcf, 3%), and vehicle fuel (.03 Bcf, <1%) (Horton).

1.3 Properties of Gasoline & Jet Fuel

Gasoline is a transparent liquid consisting mostly of organic compounds that is obtained by the fractional distillation of petroleum. It contains about 132×10^6 joules of energy per US gallon, which is equivalent to 125,000 BTU or 36,650 watt-hours (Brain). Some of the main components of gasoline are isooctane, butane and 3-ethyltoluene. Depending on the method used to produce the gasoline, it can be composed of added chemicals and materials like olefins or aromatics. These additional materials have a large effect on the octane number of the fuel (Dabelstein, Reglitzky, Schütze, & Reders, 2007). The octane rating of gasoline measures its ability to resist engine knock, a rattling or pinging sound that results from premature ignition of the compressed fuel-air mixture in one or more cylinders (The Low-Down on High Octane Gasoline, 2003). The higher the octane number the more compression the gas can handle before it ignites which means that engines can burn fuel more efficiently when using higher rated gasoline.

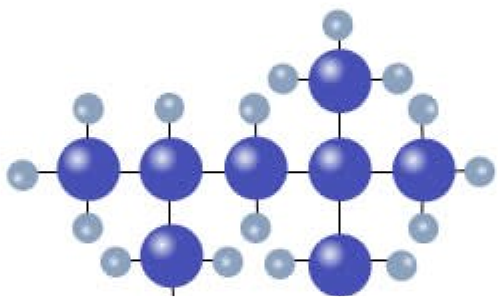

Figure 1: Gasoline Molecule

typical gasoline - C_8H_{18}

Figure 1: Gasoline Molecule (Wolfe, 2011)

Jet fuel, on the other hand, is a kerosene-based fuel that is used in aircrafts. Jet A is the type of fuel used in the United States while most of the world uses Jet A-1. The difference between the two is that Jet A-1 has a lower freezing point (-47˚C) than Jet A (-40˚C). However, due to its higher freezing point, a percentage more of Jet A can be produced compared to Jet A-1 (Aviation Fuel Industry). Gasoline by comparison has a freezing point of -40˚C which is the same as that of Jet A (Properties of Fuels, 2011).

The major difference between jet fuel and gasoline, other than the kerosene-base, is that jet fuel is more highly refined and has a higher octane rating. The refining takes out most of the light volatile compounds that could boil in low atmospheric pressures along with the heaviest compounds that tend to clog carburetors and fuel injectors (Aviation Fuel Industry).

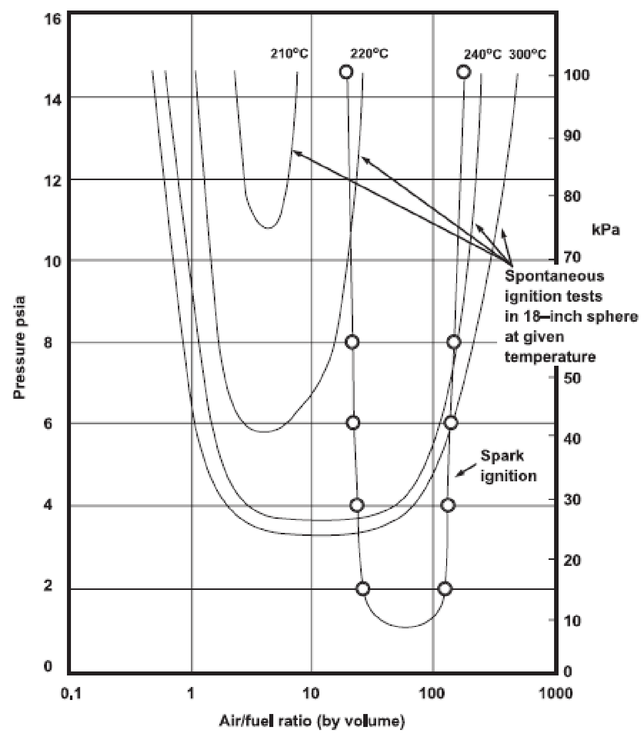

Figure 2: Auto-Ignition Tests (Properties of Fuels, 2011)

The auto ignition temperature is the lowest temperature at which a material will spontaneously ignite in a normal atmosphere without an external source of ignition (Fuels and Chemicals-Autoignition Temperatures). Gasoline has an auto ignition temperature of around 257˚C while Jet A has an auto ignition temperature ranging from 210˚C to 300˚C (See Figure 2) (Properties of Fuels, 2011).

1.4 Fuel Production/Oil Refining

Most of the fuels used in the transportation sector are produced via the same overall process, which can be broken down into four smaller processes; exploration, well development, fuel production, and site abandonment. Exploration is simply the act of searching for oil deposits that exist beneath the Earth's surface, whether by prospecting, exploratory drilling, or more sophisticated methods. Once a deposit is found, one or more wells are developed so that the crude oil may be extracted in a way that is economically viable. The crude oil pumped from the crust is then processed at a refinery and the wells are plugged once the oil deposit is effectively depleted.

Crude oil, or petroleum, is a complex mixture of carbon- and hydrogen-containing compounds, which exists as a liquid in the Earth's crust (Ophardt, Distillation Oil Refining, 2003). Petroleum must be processed in some way in order to separate its various components into fuels and other materials which include gasoline, jet fuel, home heating oil, and asphalt to name a few. The first refining process used to do this is known as "Fractional Distillation". Crude oil is heated and specific compounds boil off at different temperatures and are separated and re-condensed within a distillation tower. Within the tower, temperature decreases as height increases and separation occurs because the boiling point of a hydrocarbon

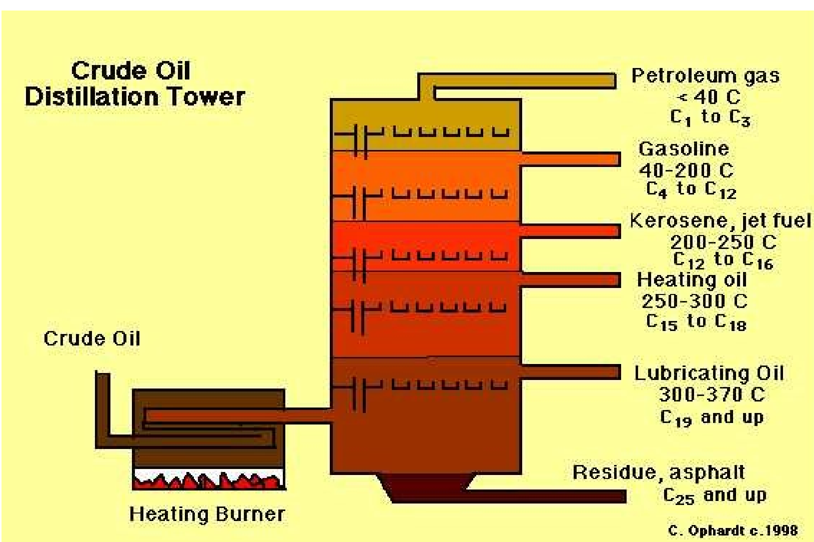

Figure 3: Crude Oil Distillation Tower (Ophardt, Distillation Oil Refining, 2003)

corresponds to the length of its carbon chain. These differences are what allow each component of the petroleum to be drawn from the distillation tower separately. The entire process is illustrated in Figure 3 along with some examples of refined components of crude oil (Ophardt, Distillation Oil Refining, 2003).

When we consider the transportation industry, the first mode of transportation that comes to mind is the automobile. In the United States the majority of our cars run on gasoline and so when oil is refined, the ultimate goal is to produce as much gasoline as possible. When a barrel of crude oil is put through the fractional distillation process previously described, somewhere between 25 and 35 percent of the yield is gasoline (Ophardt, Distillation Oil Refining, 2003). This percentage must be higher in order to meet national demand and there are many methods available for increasing it.

The most effective method of increasing the gasoline fraction is catalytic cracking. Large molecules of heavy heating oil produced in the initial refining can be broken down into smaller gasoline molecules, or “cracked”, using high temperatures and pressure. The opposite process can also be done, in that smaller carbon chains, specifically naphtha, can be combined to form larger gasoline molecules. This catalytic reforming is endothermic just like the catalytic cracking and uses moderate pressure and fixed bed catalysts. Reforming is less widely used compared to cracking due to a need for additional heating between reactors to maintain temperature (Ophardt, Conversion Oil Refining 2, 2003). By combining these methods and a few others in some cases, the gasoline fraction can be increased to nearly 50 percent.

In the United States, a barrel of petroleum is a standard size and measures 42 gallons. After refining, the barrel provides roughly 45 gallons of petroleum products (Administration, 2012). The products that make up the majority of these products are all fuels used in the transportation sector. Gasoline makes up the largest fraction at 19 gallons, then diesel fuel at 11 gallons, and jet fuel at 4 gallons. The other smaller fractions are shown along with gasoline, diesel, and jet fuel in the figure below:

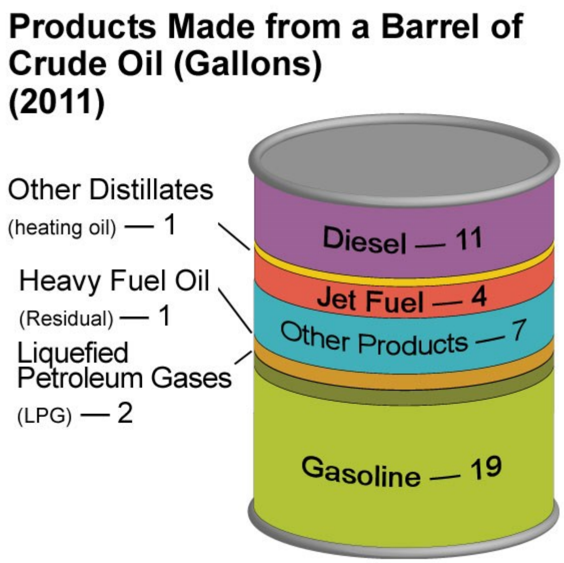

Figure 4: Yield from a barrel of crude oil (Products, 2012)

The final breakdown of transportation fuels after all stages of refining is 45% gasoline, 26% diesel, and 9.5% jet fuel.

All fuels produced through the refining processes, need one last thing before they are ready to use by the public. Each type of fuel has specific additives mixed in according to state regulations. These regulations must be followed regardless of the composition of the fuel at the end of the major refining.

1.5 What is Primus Green Energy?

Primus Green Energy is an eco-friendly fuel company based in Hillsborough, New Jersey. The company is financially backed by a primary investor, Israel Corporation Green Energy, and is actively searching for additional smaller investors. Primus claims to have created a drop-in gasoline that is competitive in price with gasoline produced from crude oil that sells for $65 dollars a barrel. While currently using natural gas as a feedstock for their production, Primus plans on eventually adjusting their process to use biomass in the form of pelletized wood waste or energy crops such as *Miscanthus* (Flexible Feedstock, Locally Sourced, 2012). The proprietary process that Primus has developed is also capable of producing other fuels that are marketable to other sectors, such as jet fuel (Millikin, 2012).

2.0 Methanol to Gasoline

2.1 MTG Process

In the MTG process, the conversion of methanol to hydrocarbons and water is essentially stoichiometric. The reaction involved in the MTG process is exothermic with a heat of reaction of about 1.74 MJ/kg of methanol. A process commercialized in New Zealand involved a fixed bed and was managed by splitting the conversion into two parts which can be seen in Figure 5.

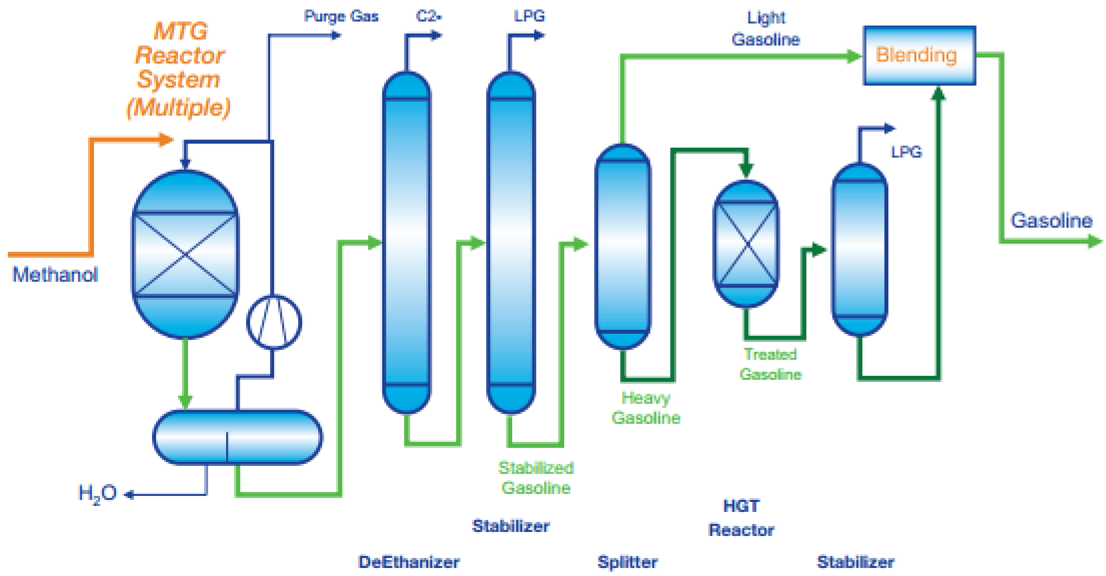

Figure 5: MTG Process (ExxonMobil MTG, 2008)

In the first part, methanol is converted to a chemical equilibrium controlled mixture of methanol, dimethyl ether, and water and as such is inherently stable. In the second step the equilibrium mixture is passed over specially designed ZSM-5 catalysts to produce hydrocarbons and water, where most of the hydrocarbons are in the gasoline range. Most of the gas is mixed with the equilibrium mixture before it is passed through the ZSM-5 reactor (Methanol to Gasoline (MTG) Production of Clean Gasoline from Coal).

MTG Gasoline vs. US Conventional Refinery Gasoline

	Summer 2005	Winter 2005	MTG Gasoline
Oxygen (Wt%)	0.95	1.08	
API Gravity	58.4	61.9	61.8
Aromatics (% Vol)	27.7	24.7	26.5
Olefins (% Vol)	12	11.6	12.6
RVP (psi)	8.3	12.12	9
T50 (F)	211.1	199.9	201
T90 (F)	330.7	324.1	320
Sulfur (ppm)	106	97	0
Benzene (% Vol)	1.21	1.15	0.3

*Oxygen is from oxygenate blending post refining.

Figure 6: US Conventional Refinery Gasoline vs. MTG Gasoline (ExxonMobil MTG, 2008)

The liquid hydrocarbon product (raw gasoline) contains mainly gasoline boiling-range material, as well as dissolved hydrogen, carbon dioxide, and light hydrocarbons (C1-C4). Essentially of the non-hydrocarbons; C1, C2, C3, and part of the C4 hydrocarbons are removed by distillation to produce gasoline that meets the required volatility specifications. The properties of MTG gasoline when compared to the average properties of conventional gasoline sold in the US in 2005 are nearly identical (see Table 1). The only noticeable difference is in MTG gasoline's lower benzene content and sulfur content of essentially zero. MTG gasoline contains 1, 2, 4, 5-tetramethyl benzene (durene) at a higher level than conventional gasoline. Durene is concentrated in the heavy gasoline fraction of a gasoline splitter and then subjected to a mild hydro-finishing process over a proprietary ExxonMobil catalyst in the heavy gasoline treater. The product is obtained in nearly quantitative yield with virtually unaltered octane but with greatly reduced durene content (ExxonMobil MTG). High levels of durene are undesirable because it can cause carburetor "icing" because of its high melting point (Packer, 2008).

2.2 Mobil's Attempts to Commercialize During the 1980s

Mobil was an American multinational oil and gas corporation that merged with Exxon in 1999 to create what is now known as ExxonMobil. Mobil discovered and patented the methanol-to-gasoline process in the 1970's and commercialized the technology in New Zealand in the 1980's. The first MTG plant was operated in New Zealand from 1985 to 1997. This New Zealand operation was considered a success for a world scale and was the first plant of its kind. Much of the current technology involving methanol as a bridge to gasoline is based on the MTG process developed by Mobil in the 1980's. Their first methanol unit was brought on stream on October 12th, 1985 and achieved design rate within 2 days. Only

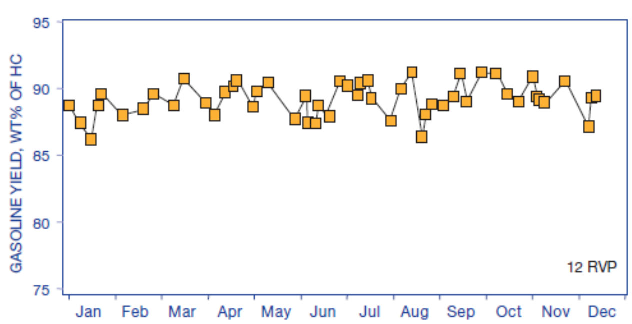

Figure 7: Commercial MTG Gasoline Yield in New Zealand Plant (ExxonMobil MTG, 2008)

five days later on October 17th the first gasoline was produced. The second methanol unit was commissioned on December 12th, and subsequently more and more units were brought on-stream and added to the process until the complex was complete and operating at 100% of the design capacity on December 27th, 1985. The MTG plant was originally a small pilot plant that ran at 500 to 1700 kg/day. Mobil scaled this pilot plant up and developed into a full-scale production plant. When compared to the estimates developed prior to the transformation of the plant; production yields, product qualities, and catalyst performance were nearly identical with their actual production. All estimates developed from the pilot plant data were consistent with those of the actual plant. According to Figure 8, the operation is very predictable and stable with only slight variation. The figure compares the average gasoline properties to the range during the first year of MTG operation. Figure 6 (in section 2.1) is a comparison of the average properties of the conventional gasoline that was produced and sold in US markets in 2005 to the MTG gasoline properties produced by the Mobil process. When compared to today's refinery gasoline, the MTG gasoline properties produced by Mobil are almost identical. The only notable differences that occur, as noted before, are that the MTG gasoline contains lower levels of benzene and essentially zero sulfur. The plant was running for 12 years and ceased operation in 1997 (ExxonMobil MTG).

	Average	Range
Octane Number, RON	92.2	92.0-92.5
Octane Number, MON	82.6	82.2-83.0
Reid Vapor Pressure, kPa	85	82-90
Density, kg/m3	730	728-733
Induction Period, min.	325	260-370
Durene Content, wt%	2	1.74-2.29
Distillation		
% Evaporation at 70° C	31.5	29.5-34.5
% Evaporation at 100° C	53.2	51.5-55.5
% Evaopration at 180° C	94.9	94-96.5
End Point, °C	204.5	196-209

Figure 8: MTG Product Properties (ExxonMobil MTG, 2008)

3.0 Primus Green Energy

3.1 Initial Plans

When Primus Green Energy was first founded, they were a green fuel initiative aiming to utilize biological feedstock in order to produce gasoline. The major selling point of their product was that their fuel could be easily integrated into current infrastructure, with no need for new engines or new fueling stations. As opposed to ethanol-based automotive fuels, their proprietary process was to be cost competitive with petroleum fuel without government subsidies. Due to reasons to be addressed later, Primus has had to alter their plans slightly and use domestic natural gas in the front end of their process as a bridge to biofuel. The company hopes to achieve its original goal of producing biofuel in the near future with changes in the automotive fuel market.

3.2 Patents

Three patents have been applied for by Primus Green Energy since 2010. The first was applied for in November of 2010 and outlines the proprietary process referred to on their company webpage. The other two were applied for in May of 2011 and are for specific parts in their reactors. Of the three patents, the first is of the most consequence. It is entitled "Single Loop Multistage Fuel Production". A four stage reactor system is described with each performing a specific task aided by a catalyst specifically chosen in each stage. The first stage uses a CuO/ZnO catalyst to convert synthesis gas to methanol and water. The methanol is then passed into the second stage, where it is converted to dimethyl ether using a gamma-alumina catalyst. Both methanol and dimethyl ether are converted into fuel and heavy gasoline in the third reactor of the series by ZSM-5. In the final stage, nickel oxide is used to convert the heavy gasoline to isoparaffins, naphthenes, and other aromatics. Exiting this stage the products are passed through a separator to form four separate streams; one stream each for fuel, water, unreacted synthesis gas, and a recycle stream to route some of the unreacted synthesis gas back into the first reactor.

The entire reactor series outlined is essentially Primus' own variation of existing technology. Mobil was the pioneer company for the conversion of methanol to gasoline and many companies, including Primus, have worked to improve on it. As far as the front end of the reactor series, existing processes exist for creating synthesis gas and using it in the production of commercial quality fuels. Primus claims that its process is unique and distinct from the prior art in the industry. This is due to the fact that their entire process operates at elevated pressures in order to yield higher efficiencies specific to transportation fuels.

To summarize their invention, Primus will be using a four reactor system in order to directly produce gasoline and jet fuel from synthesis gas. They can produce the synthesis gas to enter their system using a variety of materials including natural gas, coal, and various forms of biomass. After passing through the reactors, a recycle loop is used to enhance conversion and act as a heat sink for the reactions of each stage. The stages are preferably connected with heat exchangers in order to adjust output temperatures to ideal input temperatures (Fang, 2010).

3.3 Why Biomass?

Primus' proprietary process can use various input feedstock, including natural gas and biomass, but biomass is the intended source of the future for the company. At the current moment, natural gas is readily available in the United States at incredibly low prices so Primus has decided to use natural gas as their feedstock as they continue to develop their biomass gasification technology further (Primus Green Energy, Inc., 2012). That being said, biomass has many advantages over natural gas looking to the future.

Primus plans to make use of biomass in the form of pelletized wood waste or any of a variety of energy crops. Biomass contains stored energy due to the life process of photosynthesis (Alternative Energy). Due to the fact that biomass comes from a vast variety of sources, it is readily available in almost any area of the globe. This is an advantage for companies like Primus who are looking to utilize biomass as feedstock, enabling them to select a location for a processing plant without having to worry too much about cost of transporting biomass to the site. Pelletized wood and other forms of wood waste can be purchased from almost any mill, while most energy crops can be grown on less than ideal land tracts.

Energy crops, specifically perennial grasses, are a much more attractive source of feedstock for companies like Primus, as opposed to pelletized wood. More energy must be used in order to form the wood pellets and this detracts from the overall energy balance of the process. Perennial grasses, on the other hand, can be dried naturally and then utilized directly through the gasification process that Primus is perfecting. *Miscanthus* and switchgrass are two such grasses that are mentioned often when referring to energy crops. These hardy grasses can be grown for multiple growing seasons, 15 to 20 years, and grow very rapidly in warmer climates, while also coping effectively with a range of climate conditions (Weih). Primus has the option of constructing their commercial plant in an area with a plentiful source of natural gas nearby, while also having the opportunity to make use of any nearby vacant land to grow an energy crop such as *Miscanthus* even if the land is not of normal farm quality. Shrubs and trees such as poplar or shrub willow are also viable options as a biomass source, with similar benefits to the perennial grasses. The only downside to shrubs and trees is that the harvesting process requires more specialized equipment as compared to the harvesting process for grasses (Weih).

Biomass has potential as a feedstock for alternative fuel production and if Primus can perfect its gasification technology, we may see its potential firsthand in the near future. For the time being, natural gas should serve as a viable bridge until this process is complete and Primus is on its feet with a commercial plant up and running.

3.4 Predicted Yield & Impact on Transportation Sector

With the massive amount of gasoline consumed in the United States annually, it is a daunting task to even begin addressing the possibilities for gasoline alternatives. There have been many companies before Primus that have simply been overwhelmed by the sheer volume of product required to make an impact, despite having fully functional processes on a smaller scale. In order to evaluate Primus' potential, the claims and data attained from their small scale testing were extrapolated and compared to United States consumption.

Primus claims that when their process is scaled up to their planned commercial plant, they will be able to produce between 25 and 27 million gallons of gasoline annually per plant.

For our purposes, the high-end value of 27 million gallons was used to calculate a prospective "maximum" impact that Primus would be able to make on U.S. gasoline consumption. According to Nan Li, a member of the business development team at Primus, tests have repeatedly shown a yield of 32% conversion by weight of biomass to gasoline (see Appendix B). Using these figures and various weight conversions, the extrapolation in Equations 1, 2, and 3 was carried out in order to determine how much biomass Primus would require for each day that the commercial plant operates.

$$27{,}000{,}000\,\frac{gal}{year} * \frac{6.00\ lb}{1\ gal} * \frac{1\ ton}{2000\ lb} = 81{,}000\,\frac{tons\ gasoline}{year} \qquad (1)$$

$$81{,}000\,\frac{tons\ gasoline}{year} = 0.32 * (x\ tons\ biomass) \qquad (2)$$

$$x = 253{,}125\ tons\ biomass/year$$

$$\frac{253{,}125 tons}{365 days} \approx \boldsymbol{690\ tons\ biomass/day} \qquad (3)$$

If one commercial plant constructed by Primus would require 690 tons of biomass per day, we must then address the question of whether or not this amount is attainable.

The primary biomass feedstock referred to by Primus is *Miscanthus*. As mentioned earlier, *Miscanthus* is a hearty, perennial grass that can grow in a multitude of climates. Based in Hillsboro, New Jersey, Primus may decide to construct a commercial plant in the northeast United States so that it is close to their headquarters. There are enough sources of the alternative feed source, natural gas, in that region that this possibility is not unreasonable. If Primus were to grow *Miscanthus* in the northeast to reduce transportation costs to their plant, there are over 2.8 million hectares of idle or surplus farmland that would be suitable to perennial energy crops (NEWBio, 2012). One hectare is equal to roughly 2.471 acres, so that means that there are about 7 million acres available in the northeastern US for possible *Miscantus* growing and harvesting. According to a study conducted at Iowa State University, one acre of *Miscanthus* can yield between 10 and 15 tons of biomass every year (Heaton). Again, using the high end of the range, the acreage needed to yield 690 tons per day for Primus' commercial plant is calculated below in Equation 4.

$$690\,\frac{tons}{day} * \frac{1\ acre}{15\left(\frac{tons}{year}\right)} * \frac{365\ days}{1\ yr} \approx \mathbf{17,000}\ \boldsymbol{acres} \tag{4}$$

Compared to the theoretically available 7 million acres of land, it is very reasonable to think that Primus could obtain 17,000 acres of land from which they can harvest the necessary 690 tons per day. For comparison, the land area of Worcester, Massachusetts is roughly 37.6 square miles which converts to around 24,000 acres (Worcester, Massachusetts, 2012). It is important to keep in mind that they would also need to store the dried biomass after harvest for the year of activity, because the *Miscanthus* would only be harvested once each year.

As Primus will be building one commercial plant after acquiring data from their demonstration plant, it is important to analyze the projected impact of this single plant in replacing a fraction of the United States gasoline consumption. In Section 1.2, it was stated that 367.08 million gallons of gasoline were consumed per day on average in the United States. Using this figure, we can calculate the percentage of the total that Primus would be replacing with their single commercial plant, assuming it will produce 27 million gallons each year:

$$27{,}000{,}000\,\frac{gal}{yr} * \frac{1yr}{365\ days} \approx 74{,}000\ gal/day \qquad (5)$$

$$\frac{74{,}000\ gal}{367{,}080{,}000\ gal} \approx \mathbf{0.02}\%\ of\ US\ daily\ usage \qquad (6)$$

As expected, one single plant will not make any sort of sizable impact on United States consumption but this does not mean that Primus' technology is not worth exploring.

The most ideal situation that could be presented to a biomass initiative would be having access to an incredibly vast amount of land on which to cultivate energy crops. As it so happens, the United States Department of Agriculture runs a program through their Farm Service Agency that promotes the conservation of environmentally sensitive land (Farm Service Agency, 2013). The program pays farmers to keep tracts of land unused for a set period of time in the interest of conservation. In order to project Primus' impact further, we can estimate the fraction of gasoline consumption in the United States if they could derive from harvested biomass from the entire 27.1 million acres of land that is unused due to the Conservation Reserve Program (Barbarika, 2013). This calculation is shown in Equations 7-10, using *Miscanthus* as the energy crop being cultivated.

$$27{,}100{,}000\ acres * \frac{15\ tons\ Miscanthus}{1\ acre} = 406{,}500{,}000\ tons\ Miscanthus/yr \quad (7)$$

$$406{,}500{,}000\ tons\ Micanthus/yr * 0.32 = x\ tons\ of\ gasoline/yr \qquad (8)$$

$$x = 130{,}080{,}000\ tons\ gasoline$$

$$130{,}080{,}000\ tons * \frac{2{,}000\ lbs}{1\ ton} * \frac{1\ gal}{6.00\ lbs} = 43.36\ billion\ gallons\ of\ gasoline/yr \quad (9)$$

$$\frac{43.36\ billion}{134\ billion} * 100 = \mathbf{32.4\%\ of\ 2011\ gasoline\ consumption\ in\ US} \quad (10)$$

Under the most ideal circumstances available in the United States, Primus could replace just over 30% of the gasoline consumed in the course of 2011 using the biomass yielded from all land in the Conservation Reserve Program. This figure is extremely impressive and speaks to both how effective Primus' process is at the current state of development and also the incredibly large amount of gasoline that the United States consumes as a whole.

$$\frac{43.36\ billion\ gallons\ per\ year}{27\ million\ gallons\ per\ year} \approx 1{,}606\ plants\ (11)$$

Replacing $\pm 30\%$ of the gasoline that the transportation sector use would be an impressive figure, however it would require 1,606 identical plants and full access to all 27.1 million acres in order for Primus to produce this quantity of fuel.

Although Primus Green Energy is still in its early stages of development, the data they have collected on their proprietary process is a promising step in the right direction. There will always be unforeseen changes when increasing the scale of any initiative but at the current moment, Primus has a fair amount of potential in making an impact in the realm of alternative fuels.

4.0 Comparison to Other Companies

4.1 KiOR

According to the calculations in the Wood-To-Oil IQP research paper (Aye-Addo, Malaver, da Vitoria, & O'Connor); KiOR's potential output could be a total of 83,750 barrels of petroleum per day from a combination of 40 plants. By their estimates, that would replace

0.71% of U.S. Petroleum consumption per day. The same IQP team also claimed that Primus will only produce 208.7 barrels of oil per day which is only about 0.0015% of the consumption per day.

Primus itself reports that its first commercial plant is expected to produce approximately 3,082 gallons per hour or 1,761 barrels per day of gasoline. Dividing the Wood-To-Oil's calculation by 40 to compare one KiOR plant to one primus plant (~2094 barrels per day per plant of petroleum)

$$\frac{83{,}750\,\frac{barrels}{day}}{40\;plants} = 2{,}093.75\,\frac{barrels}{day}\,of\ petroleum * 42\,\frac{gallons}{barrel} \approx 88{,}000\,\frac{gal}{day}$$

$$88{,}000\,\frac{gal}{day} * 19\;gal\,\frac{gasoline}{42\,\frac{gal}{barrel}} \approx 40{,}000\,\frac{gal}{day}\,of\ gasoline$$

and using 19 gallons of gasoline from every one barrel of oil as shown in figure 4, one KiOR plant is estimated to produce 40,000 gallons of gasoline, or about 952 barrels, per day. (Boyajian, 2012).

Ignoring the refining that KiOR's petroleum must go through before it can be used for automobiles and the worth of the by-products that are produced when extracting gasoline from petroleum, Primus predicts to produce a little less than twice what KiOR expects to produce.

KiOR's biomass source is Southern Yellow Pine and, according to the Wood-To-Oil group, enough exists to make KiOR's efforts sustainable. Primus estimates that it will use 690 tons per day per plant while each KiOR plant needs 1500 bone dry tons per day.

KiOR:

$$\frac{40{,}000\ gallons\ gasoline}{1500\ tons\ biomass} \approx \frac{27\ gallons\ fuel}{ton\ biomass}$$

Primus:

$$\frac{3{,}082\ gallons\ gasoline * 24\ hours}{690\ tons\ biomass} \approx \frac{107\ gallons\ gasoline}{ton\ biomass}$$

As shown above, each Primus plant requires less biomass and produces more gasoline per ton of biomass than KiOR. Additionally Primus is more flexible towards what is used for feedstock, which may make Primus plants more desirable to build or invest in than KiOR (Aye-Addo, Malaver, da Vitoria, & O'Connor).

4.2 Changing World Technologies (CWT)

Changing World Technologies (CWT) is a rival company to Primus Green Energy that produces renewable diesel fuel oil from agricultural wastes such as fats, oils, greases, feathers, offal, animal carcasses, and other organic-rich wastes. This waste is used to produce renewable diesel, fertilizer and specialty chemicals. CWT is a privately held company that was founded by Brian S. Appel in 1997. Appel is currently the company’s CEO and also oversees CWT’s subsidiaries. CWT has 2 subsidiaries, it’s primary one being Renewable Environmental Solutions, LLC (RES) and the other being Thermo-Depolymerization Process, LLC (TDP). CWT has developed a process called the “Thermal Conversion Process,” (TCP) in which they use a thermal depolymerization technology. The TCP process works with wet mixed feedstocks which use water to prevent the energy penalty of drying the materials. CWT claims that the TCP is more than 80% energy-efficient with all types of carbon-based feedstocks tested, which allows it to use less energy than alternative methodologies. The company was started with the intention to commercialize this technology that produces biofuels. CWT currently has many extensive patents in the US and around the globe that cover the use of their technology in areas such as agricultural waste (offal) and mixed plastics. The company's demonstration plant is located in Missouri, where the renewable diesel fuel oil is currently produced although all of the research, development, and deployment work takes place at their pilot plant in Philadelphia, Pennsylvania. This work includes refining the company's production processes as well as developing capabilities to produce renewable diesel fuel oil from other various waste materials (Changing World Technologies, 2012). In 1998 one of CWT's subsidiaries (TDP) developed a demonstration and test plant for their thermal depolymerization technology in Philadelphia, Pennsylvania as well. After CWT and its three subsidiaries filed for chapter 11 bankruptcy in March of 2009 due to a failed initial public offering (IPO) attempt that February, the company reorganized and emerged from bankruptcy in May 2010. CWT's renewable diesel fuel oil was designated as both a biomass diesel and advanced biofuel in 2011 under the EPA's Renewable Fuel Standards Program (RFS) (Lemley & Kaufman, 2006).

4.3 NEWBio

NEWBio or Northeast Woody/Warm-season Biomass Consortium is an association of companies and organizations involved in the development and sustainable production of regionally appropriate biomass feedstocks. Led by Penn State's College of Agricultural Science, it is backed by a grant of almost $10 million from the US Department of Agriculture's National Institute of Food and Agriculture. Other consortium partners include a mix of universities and industrial collaborators with Primus being the only advanced alternative fuel company of the group.

NEWBio will focus on the development of four large demonstration projects throughout the Northeast operating at commercial scales of thousands of acres to produce between 500 and 1,200 tons per day of lignocellulosic biomass for alternative fuel production. Plant scientists will work to improve the ability of crops to grow on marginal lands and to resist insects and disease, with a goal of increasing yields by 25 percent and reducing costs by 20 percent (Pasolini, 2012). Another one of the consortium's primary goals is to utilize marginal and abandoned lands in order to optimize the growth of dedicated short rotation woody crops and warm season grasses. They intend to identify new ways to create sufficient management of SRWC and perennial grasses; to establish strategies for biomass harvest that will create a safer, more efficient and more effective system; and to develop processes that will maximize feedstock value for commercial partners such as evaluating the characteristics of the biomass and supplying chain transformations. By following these goals the consortium aims to be a tool to assess the role of biomass production and policy on economic and community development, along with creating a bright future for the alternative energy field by engaging the next generation of scientists, entrepreneurs, employees, and citizens through science based research, education and outreach. The consortium has also tried to broaden its horizons by collaborating with many commercial partners who have established breeding programs. These partners provide the biomass feedstocks that the consortium finds necessary for their projects. The two biomass feedstocks that will be focused on in order to fulfill the aforementioned objectives are short rotation woody crops (willow and poplar), and perennial warm-season grasses (switchgrass and *Miscanthus*) that can be grown on marginal agricultural land. Primus Green Energy joined the consortium as an industry collaborator in November of 2012. Despite using natural gas as a feedstock currently, the future research and developments reached by NEWBio should be beneficial when Primus decides to switch to biomass (Boateng, 2012).

4.4 Synthetic Genomics

With numerous companies researching alternative fuel sources, Synthetic Genomics is currently developing genetically engineered algae that yield bio-oil through its natural photosynthesis processes. Many preliminary tests have shown promise, with an extrapolated yield projection of 2000 gallons of fuel per acre in one year's time. Their research has drawn significant interest from ExxonMobil who plans to invest 600 million dollars in the technology, with half going directly to Synthetic Genomics and the other half being spent within ExxonMobil itself (Next Generation Algal Biofuels Fact Sheet, 2012).

The prospect of using algae as a feedstock is very intriguing for a multitude of reasons. Algae can be grown on land or in water that is unsuitable for any crop or food product, allowing it to be grown virtually anywhere in the United States or elsewhere. Additionally, large quantities of algae can be grown quickly, facilitating rapid testing of different strains during the research period. Synthetic Genomics is working towards producing a strain that produces bio-oil through photosynthesis and allows for easy recovery of the aforementioned oil. Photosynthesis is the ideal production method for bio-oil in that it benefits the environment by consuming CO_2 and produces oxygen in addition to the oil. At the current stage of their research, Synthetic Genomics had engineered algal cells that secrete oil continuously through the cell wall and these oils resemble crude oil in their molecular structure (Next Generation Fuels & Chemicals, 2012).

The next step that Synthetic Genomics looks to overcome, is finding an efficient way to separate the algal cells from the secreted bio-oil. It is reasonable to believe that a process such as Primus' could potentially make use of the oil rich algae as a feedstock for a fuel production process. Primus claims that their proprietary process can use a variety of energy crops as input, with no specific limitations provided. The only foreseeable issue could be water content, but it is worth exploring due to the evidence of the astounding oil yield of algae. In a previous IQP study conducted on Biomass Conversion to Liquid Fuels, Berk Akinci extrapolated the oil yield of various plant oils and microalgae was the highest yielding oil (see Figure 9 below), with almost three times that of its closest contender which was oil palm (Akinci, 2002). There has been no confirmation from Primus on whether their process could make use of algae as a feedstock, but nonetheless it is an intriguing possibility.

Table 2.3 Oil yields of various plant species[131], their energy yield and land area needed for their cultivation so satisfy the U.S. 1999 total energy demand. Energy content extrapolated from USDA's *Nutrient Database*.[132]

Plant	Species	Oil Yield kg/(km^2*yr)	Energy content MJ/kg	Energy Yield * J/(km^2*yr)	Land area needed * km^2	% US Land needed * %
Corn	*Zae mays*	14,500	36.99	5.364E+11	188,214,895	2055%
Cashew nut	*Anacardium occidentale*	14,800	36.99	5.475E+11	184,399,728	2013%
Oat	*Avena sativa*	18,300	36.99	6.769E+11	149,132,021	1628%
Palm	*Erythea salvadorensis*	18,900	36.99	6.991E+11	144,397,671	1577%
Lupine	*Lupinus albus*	19,500	36.99	7.213E+11	139,954,666	1528%
Rubber seed	*Hevea brasiliensis*	21,700	36.99	8.027E+11	125,765,713	1373%
Kenaf	*Hibiscus cannabinus L.*	23,000	36.99	8.508E+11	118,657,216	1296%
Calendula	*Calendula officinalis*	25,600	36.99	9.469E+11	106,606,093	1164%
Cotton	*Gossypium hirsutum*	27,300	36.99	1.010E+12	99,967,618	1091%
Hemp	*Cannabis sativa*	30,500	36.99	1.128E+12	89,479,212	977%
Soybean	*Glycine max*	37,500	36.99	1.387E+12	72,776,426	795%
Coffee	*Goffea arabica*	38,600	36.99	1.428E+12	70,702,486	772%
Linseed	*Linum usitatissimum*	40,200	36.99	1.487E+12	67,888,457	741%
Hazelnut	*Corylus avellana*	40,500	36.99	1.498E+12	67,385,580	736%
Euphorbia	*Euphorbia lagascae*	44,000	36.99	1.628E+12	62,025,363	677%
Pumpkin seed	*Cucurbita pepo*	44,900	36.99	1.661E+12	60,782,093	664%
Coriander	*Coriandrum sativum*	45,000	36.99	1.665E+12	60,647,022	662%
Mustard	*Brassica alba*	48,100	36.99	1.779E+12	56,738,378	619%
Camelina	*Camelina sativa*	49,000	36.99	1.813E+12	55,696,244	608%
Sesame	*Sesamum indicum*	58,500	36.99	2.164E+12	46,651,555	509%
Crambe	*Crambe abyssinica*	58,900	36.99	2.179E+12	46,334,736	506%
Safflower	*Carthalmus tinctorius*	65,500	36.99	2.423E+12	41,665,893	455%
Buffalo gourd	*Cucurbita foetidissima*	66,500	36.99	2.460E+12	41,039,338	448%
Rice	*Oriza sativa L.*	69,600	36.99	2.575E+12	39,211,436	428%
Tung oil tree	*Aleurites fordi*	79,000	36.99	2.922E+12	34,545,772	377%
Sunflower	*Helianthus annuus*	80,000	36.99	2.959E+12	34,113,950	372%
Cocoa	*Theobroma cacao*	86,300	36.99	3.192E+12	31,623,592	345%
Peanut	*Arachis hypogaea*	89,000	36.99	3.292E+12	30,664,224	335%
Opium poppy	*Papaver somniferum*	97,800	36.99	3.618E+12	27,905,071	305%
Rapeseed	*Brassica napus*	100,000	36.07	3.607E+12	27,987,247	306%
Olive tree	*Olea europaea*	101,900	36.99	3.769E+12	26,782,296	292%
Piassava	*Attalea funifera*	111,200	36.99	4.113E+12	24,542,410	268%
Gopher plant	*Euphorbia lathyris*	111,900	36.99	4.139E+12	24,388,883	266%
Castor bean	*Ricinus communis*	118,800	36.99	4.394E+12	22,972,357	251%
Bacuri	*Platonia insignis*	119,700	36.99	4.428E+12	22,799,632	249%
Pecan	*Carya illinoensis*	150,500	36.99	5.567E+12	18,133,661	198%
Jojoba	*Simmondsia chinensis*	152,800	36.99	5.652E+12	17,860,707	195%
Bassu palm	*Orbignya martiana*	154,100	36.99	5.700E+12	17,710,032	193%
Jathropha	*Jathropha curcas*	159,000	36.99	5.881E+12	17,164,251	187%
Macadamia nut	*Macadamia terniflora*	188,700	36.99	6.980E+12	14,462,724	158%
Brazil nut	*Bertholletia excelsa*	201,000	36.99	7.435E+12	13,577,691	148%
Avocado	*Persea americana*	221,700	36.99	8.201E+12	12,309,950	134%
Coconut	*Cocos nucifera*	226,000	36.99	8.360E+12	12,075,734	132%
Oiticia	*Licania rigida*	252,000	36.99	9.321E+12	10,829,825	118%
Buriti palm	*Mauritia flexuosa*	274,300	36.99	1.015E+13	9,949,384	109%
Pequi	*Caryoca brasiliense*	314,200	36.99	1.162E+13	8,685,920	95%
Macauba palm	*Acrocomia aculeata*	377,500	36.99	1.396E+13	7,229,446	79%
Oil palm	*Elaeis guineensis*	500,000	36.99	1.850E+13	5,458,232	60%
Microalgae	*(ASP Experimental Yield)*	1,460,124	36.99	5.401E+13	1,869,098	20%

* Results calculated from values in this table (also given U.S. 1999 total energy consumption and U.S. total land area.)

Figure 9: Oil Yields of Various Plant Species (Akinci, 2002)

5.0 Conclusions

The goal of this project was to assess the validity of claims made by alternative fuel company Primus Green Energy. A secondary goal of this project was, while assuming the claims were true, to assess the impact of Primus Green Energy on the transportation sector. All information used in this assessment was accessed in the public domain and due to the proprietary nature of the fuel-production process, the legitimacy of the data was analyzed from a feasibility standpoint alone. The conclusions and recommendations we have arrived at are tentative as the announced opening of Primus' first demonstration plant is sometime in April 2013.

With gasoline being as expensive as it currently is, there have been numerous attempts to replace petroleum-derived gasoline with more cost-effective alternatives. Primus claims to have produced a cheap synthetic gasoline that can be sold for as low as $65 per barrel. Using the output numbers that Primus has provided, it was calculated that a single Primus plant could produce approximately 1,761 barrels of gasoline per day which would replace about 0.02% of the gasoline used in the US's transportation sector daily. While this may not look too impressive, if Primus was able to use all 27.1 million acres of land unused due to the Conservation Reserve Program, the output that Primus claims could replace ≈30% of the amount of gasoline used for the transportation sector. While this is an impressive figure, building the 1,606 plants which would be required to process that large amount of biomass is unrealistic.

Therefore we have concluded that Primus, although making innovative steps towards a solution to the United States' problem with oil, could not make a substantial impact on the oil economy, either nationally or internationally with their planned plant size regardless of the feedstock used. That being said, it is plausible that their process could be beneficial to a small area of the country or possibly in the fueling of vehicles belonging to a company or corporation. Any impact seen by Primus Green Energy with their current plans and statistics will most likely be found on a very small scale.

Appendix A: Interview with Todd Keiller (Keiller, 2012)

- Provisional patents can be resubmitted, as long as no public disclosure has been made. Once a utility patent is applied for, additional discoveries related to the original idea can be covered under patents called continuation or divisional patents.
- Patents expired 17 years from date of issuance before the 90's, and changed to 20 years from date of application after that.
- A divisional or continuation patent can be filed if there is something new to add. These can create a family tree of patents.
- In a family tree of patents, the expiration goes from the date of the newest patent application.
- Improvements on patents can be patented. However, licensing may be needed should the original patent still be valid.
- When a new use is discovered for an existing patent the patent holder has the option to license the idea but they also have the ability to block the new use.

- Upon filing a single attorney will be assigned to the case. If the requester is unsatisfied they may switch attorneys. There is usually one examiner assigned to the patent but an appeal to their supervisor can be made if the requester believes they are not getting anywhere with the original examiner.
- The examiner will have some background in the subject but may not be specific (ex: general chemical engineering).

Appendix B: E-mail Exchange with Nan Li, Business Development, Primus Green Energy (Li, 2012)

- Why have you set biomass aside and does it look to be only temporary?

  Answer: Our proprietary technology that confers the greatest business advantage and produces a very high quality fuel lies in the conversion of syngas to fuel (STG+). The source of the syngas is immaterial to that process, it could be biomass or natural gas, or landfill gas or a host of other sources. We are using Natural gas first because of low cost of the feedstock, relatively low cost and high availability of conversion technologies to make syngas from NG, and its wide geographic availability, permitting us more flexibility in siting our first plant. It is important to reduce technological and financial uncertainties as much as possible in the first commercial plant, and NG is therefore a key component.

  We continue to look for a scalable gasifier that can produce the quantities and quality of syngas that we require for the STG+ process. This is being done in parallel but as a secondary priority. We have a gasifier that works at small scale, it will take additional time and financial resources to scale up. We expect to revisit biomass gasification next year.

- In this article (Ostfeld, 2012) Dr. Boyajian stated that your process yields are in the range of 27-33% by weight of biomass to gasoline. Is this figure accurate? And what is the conversion rate for your jet fuel production?

  Answer: The figure is correct . . . we have repeatedly reached 32% conversion. Jet fuel will be approximately the same.

- Are there any other benefits to using natural gas other than its current low price and availability? If so, what are they?

  Answer: Ease of handling, availability of syngas conversion technologies from a variety of vendors.

- Do you use parallel catalytic beds in order to allow the catalysts time to re-activate? If yes, how many?

  Answer: If you were asking about catalyst regeneration, yes, we use two sets of reactors to allow catalyst regeneration in order to maintain continuous operations (one reactor is online while the other is being regenerated).

- Could micro-algae be a potential feedstock for your process?

  Answer: Yes. Our STG+ process produces high quality liquid fuels from synthesis gas so we can potentially use any feedstock that can be converted into synthesis gas. Microalgae can be gasified to produce synthesis gas so it is a potential feedstock for our STG+ process. Our R&D team has [been] exploring many different biomass sources including microalgae.

- Is the energy balance of your plant net-positive?

  Answer: It depends on the configuration of the specific plant.

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